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Improvement in Drag & Control Characteristics of Hypersonic Vehicles Through the Use of the Nonlinear Properties of the Enveloping Plasma

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13. Abstract (Maximum 200 words)

When we first reported our ideas about the role of vorticity in plasma-shock interactions at 1996 Prinston AFOSR meeting, there was mixed reaction among the researchers in the field. Although some of them thought that we suggested a correct explanation of Ganguly's shock-tube experiments, others were doubtful (including Ganguly himself) and continued to believe that ionization is important for the physics involved. The past few years has seen us and other research groups (e.g. Macharet et al, Leonov et al) test our ideas, and by now it is clear and broadly acknowledged that it is the vorticity dynamics that is the key process responsible for the shock modifications and the drag reduction at moderate Mach numbers.

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Final Report

"Improvement in Drag and Control Characteristics of Hypersonic Vehicles Through the Use of the Nonlinear Properties of the Enveloping Plasma"

AFOSR F496209810320

03/01/98 – 09/30/01

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Outcome of our Research

When we first reported our ideas about the role of vorticity in plasma-shock interactions at the 1996 Princeton AFOSR meeting, there was mixed reaction among the researchers in the field. Although some of them thought that we suggested a correct explanation of Ganguly's shock-tube experiments, others were doubtful (including Ganguly himself) and continued to believe that ionization is important for the physics involved. The past few years has seen us and other research groups (e.g. Macharet et al, Leonov et al) test our ideas, and by now it is clear and broadly acknowledged that it is the vorticity dynamics that is the key process responsible for the shock modifications and the drag reduction at moderate Mach numbers.

The results of our research supported by this grant have been reported at several conferences (e.g. 1999 annual AIAA Meeting; 2nd International Workshop on Laboratory Astrophysics with Intense Lasers, Los Alamos 1998; AIAA 2000-2700 31st AIAA Plasmodynamics and Lasers Conference, Denver 2000.

The results have been published in *Physica D.* The reference is, K. Kremeyer, S. Nazarenko and A.C. Newell, "Propagation of shocks through nonuniformly heated gases", *Physica D,* **163,** pp 150-165, 2002.

Overview of the Problem

Experimental and theoretical work on the use of plasmas to reduce the drag on airplanes experienced a resurgence after the group of Klimov reported on their plasma wind tunnel experiments performed in Russia. According to Klimov et al, a significant drag reduction was observed on a cone-shaped model in supersonic flow, when plasma was added ahead of the shock.

In supersonic flows the major contribution to the drag comes from the bow shock (wave drag). Thus the attention of Klimov et al was given to measuring the shock wave modifications after the plasma injection.

The shock was observed to decay and the usually sharp jump in density at the shock front "split" into two or more smaller jumps. Motivated by Klimov et al, Ganguly et al observed shock "splitting" and damping in a shock tube containing Argon plasma.

Shock tube geometry is easier to study theoretically. However, in spite of a significant experimental progress an outstanding issue still was whether the observed shock "splitting" and attenuation are due to plasma electromagnetic effects or to the gas heating which accompanies the introduction of non-equilibrium plasmas.

Our Results

Our work on this project was not intended to model the experiments exactly. Instead, the goal was to examine the cases corresponding to a large set of initial temperature profiles which differ from each other in amplitude, characteristic width and shape. The results demonstrate the robustness of the shock "splitting" and other observed phenomena, by virtue of their low sensitivity to the detailed shape of the initial density profile.

We studied the baroclinic vorticity generated at the shock front, the instability of lagging interfaces evolving into mushroom-like structures (similar to the Richtmeyer-Meshkov instability), and the formation of quasi-1-D jet-like velocity and density profiles immediately behind the shock. Although the aim was not to reproduce the experimental results exactly, their general features were discussed and explained.

The results presented in our *Physica D paper* indicate that the experimentally observed shock "splitting" signatures can be fully attributed to the shock curving or bowing as it passes through the different transverse density profiles and associated vorticity dynamics.

Collaboration

Our research motivation was derived from experiments and not just from academic interest. Thus, during our project we thought that it was important to maintain a close contact with experimentalists. In particular, many of the numerical simulations were performed by us using the set of

parameters suggested by British experimentalists working in the area, in particular Terry Cain from DERA and Ron McEwen from BAe. This allowed us not only to enhance our theoretical understanding of the fine details of the plasma-shock interactions but also provided a theoretical guidance for planning future experiments by these groups.